The analysis of these options demonstrates that the effectiveness of the phased construction is highly dependent on the size and location of each phase in relation to the site's subwatersheds and on the ability to keep the construction on schedule. For both options the phases are aligned approximately with watershed boundaries, therefore all sedimentation basins need to be built as in the standard case. In the case of the NS option basin Bd will be replaced by two smaller basins. Total sediment delivery will be reduced if each phase is disturbed for a shorter time than for the standard case. In our computations we assume that the entire construction will take 1 year for both the standard and phased construction, but for the phased construction, each phase will be disturbed only for half a year (Table 5). Under such conditions, the total sediment delivery can be reduced to 50% of the sediment delivery for the standard scenario which is close to the estimates given in the report by CWP (1997).

The additional cost for this approach includes a more complex network of diversion ditches needed to direct flow into the basins, idle time or re-mobilization cost of the heavy equipment and longer maintenance of the finished phase. There are also numerous site-specific issues related to this approach, such as balance in cut and fill for each phase, however, for our site, cut has exceeded the fill significantly and an off-site storage was established that could have been used for the phased approach too.

4.2.3 Effectiveness versus costs for basin-based measures

In line with the discussion in section 2, we map the alternative measures by their cost and effectiveness to show which ones are "efficient" in the sense of giving the best economic performance for a given level of environmental performance, or the best environmental outcome at a given cost level. The following alternatives for the subwatershed B are considered:

1. Pre construction
2. Construction with no control measures
3. Sediment basin measures: standard, baffles, larger basins
4. Combined sediment and water quality measures
5. Phased construction

In Figure 8 (see also Tables 4 and 5), alternative 2 reflects construction without any sediment control. Alternative 3a indicates standard sediment basins, alternative 3b improves the basin efficiency using baffles and 3c replaces the two smaller basins by a single large one. Alternative 4a is similar to 3c, however the cost is significantly reduced by converting the pond to storm water control wetland (or, in other words, building the pond at the beginning of construction rather than at the end). Alternative 4b combines the large pond (future wetland) with the two sedimentation basins. Phased construction is presented by alternatives 5a and 5b.

Table 5. Phased construction scenarios: impact for the subwatershed B, Centennial Campus case study. Each phase contributes sediment for 6 months.

Scenario option	***Contrib. area*** [acre]	***Pond size: area/vol*** [sft/cf]	***Est. cost*** [$]	***Disch.*** [cft/yr]	***Sed. Yield*** [T/yr] (*total for 6mo*)	***SDR/ Effect. %***
5a. Phased EW in B						
Constr., basin in Bc	5.32	3,264/9,540	4770	201,364	49	
Undisturbed Bd	2.37	na	na	43,437	2	
Phase I total	7.69		4770	244,800	51 (*25.5*)	
Stabilized, Bc converted	5.32	na	500[4]	100,000[3]	15[3]	
Constr., basin in Bd	2.37	1,938/4,284	2142	100,389	24	
Phase II total	7.69		2142	200,000	39 (*19.5*)	
Phase management			4,000[1]			
Phase I+II total *With wetland pond**	7.69		10,912 *24,163*	222,400	**45 per year**	0.33/67%
5b. Phased NS in B						
Constr., basin Bc	5.32/2.5	3,264/9,540	4770	201,364	49	
Constr., basin Bd	2.37/1.2	1,938/4,284	2142	100,389	24	
Phase I total			6912	301,753	73 (*36.5*)	
Stabilized, Bc converted	5.32/2.8	3,264/9,540	500	100,000[3]	15[3]	
Stabilized,Bd converted	2.37/1.1	1,938/4,284	500	50,000[3]	5[3]	
Phase II total			1000	150,000[3]	20 (*10*)	
Phase management			5,000[2]			
Phase I+II total *With wetland pond**			12,912 *26,163*	225,876	**46 per year**	0.34/66%

[1] includes cost of additional ditches and re-mobilization/idle time of heavy equipment
[2] higher cost reflects need for more ditches or split of Bd into 2 smaller basins
[3] rough estimate based on the values for undisturbed conditions
[4] cost of maintenance (mowing, watering)
* the additional (excavation) cost for the pond is given separately as this is in fact a cost that should not be attributed to sediment control but to stormwater control on the site.

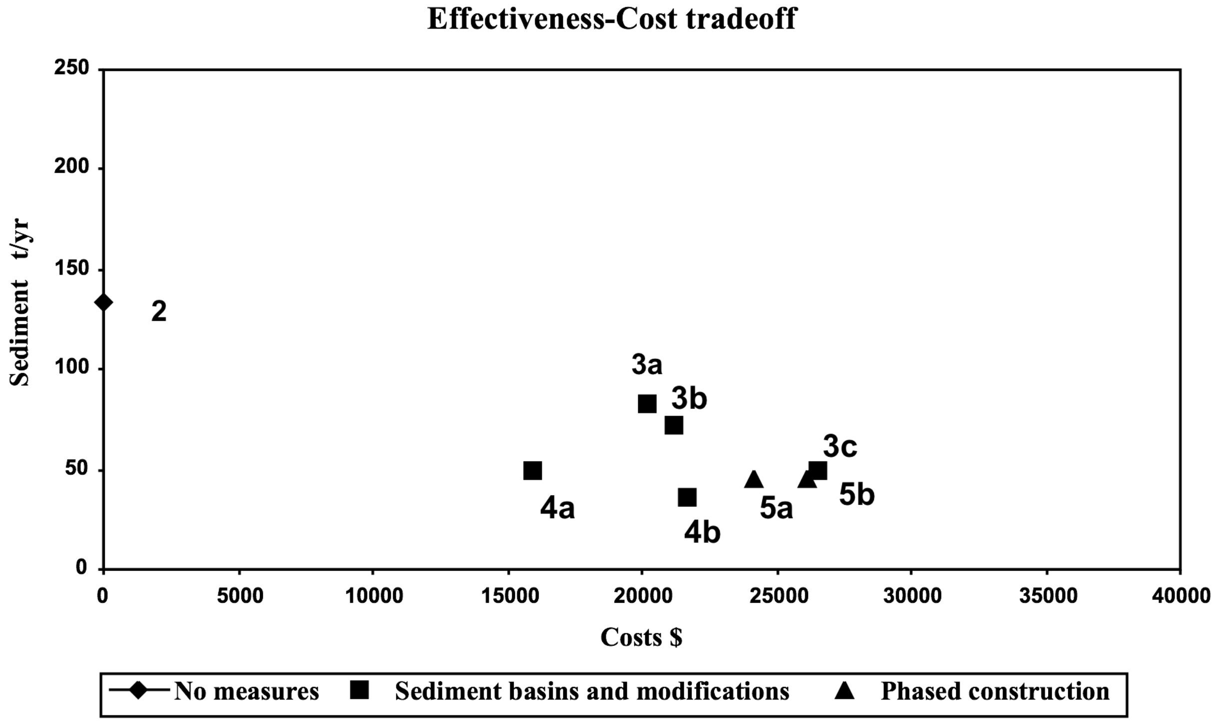

Figure 8. Effectiveness-costs trade-off curve for scenarios - Centennial Campus case study, subwatershed B. Cost includes the cost of sediment control measures and the cost of larger pond to be used for a constructed wetland as a storm water control measure.

The results in Figure 8 take on additional significance when the reduction in off-site impacts is taken into account. Sediment that ends up in off-site storm water ponds and in streams and lakes leads to ecological damages. Little is known about the monetary value of ecosystem related problems and as a proxy we use the cost that would be incurred under the assumption that in an urban setting the majority of the sediment not retained on construction sites will eventually end up in storm water ponds or water reservoirs downstream from the construction site. Under normal conditions, storm water wetlands and ponds need to be dredged every 5 to 20 years. The costs for dredging and sediment removal is site specific and varies depending upon the size and depth of the facility, the volume of sediment trapped, ease of access and whether or not on-site disposal of the dredged sediments is possible.

A large fixed cost of dredging is the mobilization and demobilization of the required machinery and personnel. For smaller wet ponds which can be drained or dredged from shore, a perimeter or dry operation will usually suffice. In this case, a backhoe or crane can scoop out the sediment and the costs of mobilizing and demobilizing will range from $5,000 to $7,000. Large wet ponds will often require a waterborne operation during which an excavator or a crane must be mounted to a floating barge and moved into position. The cost associated with such an operation is usually around $30,000. The costs of physically dredging sediment once mobilization has occurred depend on the total volume of sediment removed. The cost per cubic yard is largely influenced by the depth of the water and the distance between the excavation area and the "staging area" where sediment is transferred to trucks for removal. A further consideration is whether the equipment can easily access the bottom. Dredging costs range from $6 to $15 per cubic yard ($0.5 per cf).

Disposal costs are mainly made up of transportation costs and thus depend particularly on whether on-site disposal is available. Cost may range form $3 per cubic yard where a single truck is used to dispose of the material on-site to $30 per cubic yard for large wetlands requiring a fleet of trucks to haul the material to an off-site location.

We assumed that 85 % of sediment not retained on the building site will settle in off-site storm water ponds and wetlands. For scenario 3a this would be 70 ton of sediment. This amount of sediment is equal to 55 cy (1,496 cf assuming soil density of 1.5 g/cc or 0.0468 t/cf and 27 cf = 1cy). Assuming dredging costs of $15 per cubic yard and disposal cost of $15 per cubic yard, total off-site cost for the standard scenario 3a would be $7,650. Under scenario 4a and 4b, with sediment retention of 85% and 94 % respectively, cost for off-site dredging and removal operations will obviously be less. Notice that in calculating the off site costs, mobilization cost were not included.

Table 6. Estimated private and off site cost of the scenarios, Centennial Campus case study

Scenario	***Estimated cost for developer****	***Estimated off site costs#***	***Total***
3a: Standard basins	$6,912	$1,650	$ 8,562
3b: Standard with baffles	$7,912	$1,307	$ 9,219
4a: Use storm water pond for sediment control	$1,502	$876	$ 2,578
4b: Combine 3a and 4a	$8,070	$641	$ 8,741
5a: Phased development	$10,912	$812	$11,724

* includes cost relevant only to sediment control, storm water control cost is excluded.
# mobilization cost were not included.

5. Discussion

The use of modeling has provided an opportunity to explore a wide range of different alternatives for improvement of current sediment control practices and obtain valuable insight on how these practices compare in terms of their cost and effectiveness. Although the WEPP model was calibrated using post-construction data, not all features of the site were included in the modeling. Therefore the estimates of discharge and sediment yield are relative and serve for comparison of different approaches rather than a prediction of the actual sediment yields for the given year. It should be also noted that erosion and sediment control is highly site specific and some of the conclusions for the presented test case may not apply to sites with significantly different conditions.

5.1 Basins

The modeling confirms results of previous observations that the current size of sediment basins is not adequate for controlling the sediment transport from disturbed areas. The possible explanation may be in the assumptions that were used for the development of the current guidelines. For example, the design may be based on the concept of overflow rate (Haan, 1994) which assumes steady state, quiescent flow, a condition that is hard to achieve during storms for relatively small basins. Also, the design is based on 10 year design storm derived from long term data, while the WEPP model uses data from the closest climate station to generate series of storms (in our case for 5 years, so we may be actually underestimating rainfall intensity) - it is possible that the 10 year design storm underestimates the intensity of the storms occurring in the study area. Underestimation of 10-year discharge (Q10) can be also caused by inadequate C-factor (in our case C=0.6 for bare soil). To better understand the current guidelines for basins and suggest realistic improvements, it is important to analyze the original assumptions of the design and adjust the guidelines so that these assumptions are met, or the basin size, shape, outlet, baffles are adjusted to reflect the realistic conditions on NC construction sites.

The "real world" sediment yield from the site may be even higher than the models indicate, because the predicted increase in sediment yield was smaller than the increase observed for construction sites (5-times versus 10-500-times, see EPA 2005, Owens rt al., 2000). The WEPP model does not include several phenomena that may increase the sediment yields, such as:

- potential erosion of the basin banks (EPA 2005), commonly observed at construction sites;
- impact of unstable, turbulent flow within the basin that reduces the deposition rate (Thaxton et al., 2004)

Turbulent flow impact can be addressed by mandatory incorporation of baffles into the basin design and further investigation of the optimal basin depth, length-to-width ratio, as well as the number and distance between baffles.

The concept of overflow rate only minimally reduces the runoff from the site and the runoff rates are mostly controlled by the incoming flow rate. However, it reduces the sediment in the runoff by reducing the flow velocity within the basin. This may have an unintended consequence of significant runoff (compared to pre-construction) with reduced sediment concentration (and thus increased capacity to erode) flowing out of sedimentation basin, downstream off the site. Thus the modeling (and monitoring) of impacts should be performed beyond the construction site to assess the possibility of increased bank erosion. While the rules require keeping the runoff rates at the pre-construction levels (or below erosional levels), the design manual does not sufficiently show how to achieve it - this should be put in line with the sedimentation basin design. Integration with storm water control (its implementation at the beginning of construction) can provide a cost effective solution.

5.2 Phased construction

Phased construction limits the area that is disturbed at any given time resulting in reduced erosion and sediment transport. However, our case study demonstrates that the effectiveness of this approach is highly site specific and greatly depends on spatial patterns of disturbed areas in relations to watersheds. The capability to stay on schedule also plays an important role in reduction of total sediment delivered from the site. There are additional issues related to the construction management, such as idle time or re-mobilization of heavy equipment for each phase and spatial pattern of cut and fill that can make the phased construction complex, especially for smaller sites. Guideline for design of effective phased construction requires further study that will address the following issues:

- what is the size and type of construction site where phased construction would be the most beneficial
- what is the optimal size, shape and location of phases in relation to the site subwatersheds, cut and fill requirements and type of construction (e.g. impervious versus landscaped areas)

Phased construction would particularly benefit from the availability of GIS-based simulation tools that could help to optimize the phases in terms of their cost and effectiveness. Some of these issues are covered by Deering, (2000).

5.3 Importance of spatial aspects

In the WEPP model, the complex hillslopes and watersheds are approximated by tilted planes with rectangular shape. Sheet and rill erosion is modeled over these planes. We have found that the shape of the rectangle that is used to approximate the contributing area can significantly influence the modeling results. Wider, shorter rectangles produce less sediment than the same area approximated by a square (Table 7). In reality, the shape of the contributing area and spatial pattern of sediment transport over it can be quite complex and apparently needs to be taken into account when designing the control measures. There are no simpler rules currently available that would adjust the size of the basins based on the shape of contributing area and further research is needed to understand its impact.

The computational experiment with different shapes of hillslopes also highlights that basin effectiveness is not a very good measure for evaluating performance of a sediment control measure, as explained by Haan et al., (1994) and demonstrated by Moore (2004), because effectiveness can be high for high loads and lower for small sediment loads as in the case shown in table 7.

Table 7. Impact of hydrologic unit shape on sediment yield. Note that the efficiency for lower yields is lower, than for higher sediment yields.

Scenario	*Contrib. area*	*square*	*SDR efficiency*	*wide rectangle*	*SDR efficiency*
2. No measures					
Bc	5.32	179	1	86	1
Bd	2.37	51	1	38	1
Total	7.69	**230**	**1**	**124**	1
3a. Standard					
Basin Bc	5.32	82	0.5/50%	49	0.6/40%
Basin Bd	2.37	20	0.4/60%	24	0.6/40%
Total.	7.69	**102**	**0.4/60%**	**73**	0.6/40%

The results in Table 7 highlight some of the problems with spatially aggregated models and the need to take into account the hydrologic unit shape for proper calibration of the model. It also indicates the need for spatially distributed models that provide a more realistic incorporation of terrain influence on spatial distribution of erosion and deposition and sediment transport. Figure 10 illustrates various approximations of the study site in the WEPP, GeoWEPP and SIMWE models and the value of spatially distributed modeling at least for analysis of spatial patterns of sediment transport. While the research of spatially distributed, process based models is very active, additional features such as basins need to be incorporated to make the models fully applicable for the construction sites.

6. New technologies for design: Interactive solid landscape models

Design of various sediment control alternatives is supported by the use of CAD and GIS tools or a specialized software, such as SedCAD or SedSpec (Engel and Sullivan, 2005). The specialized software provides good capabilities for design of individual measures or systems of well defined structures. Spatial distribution of the measures on the site within the context of its watershed can be studied using GIS; however, our previous experience shows that this can be a tedious process, especially in complex landscape conditions and when larger number of alternatives needs to be explored. Recently, new systems were developed that allow the users to interact with landscape models in a more intuitive way. While these systems are still experimental, the first commercial versions are becoming available.

Several alternative systems have emerged recently (Figure 9), including:

1. **GIS2Map3D**: Solid surface with printed imagery and interactive display of GIS layers using projectors (Coucelo et al., 2005, Figure 9a). The advantage of this system is that it enables a high resolution and a large format if desired. The disadvantages are that the system is static (once carved, it practically cannot be changed, but objects can be added) and its high costs.

2. **Xeno Mark III**: Pin based system where the landscape surface is represented by movable pins covered by latex sheet. The main advantage of this system is its dynamic surface; different sites (or in case of a construction - terrain for different stages of construction) can be represented by the same system (it takes only minutes to change the surface). The disadvantages are the high cost of the hardware and maintenance requirements.

3. **Tangible GIS:** The Tangible Infoscape system called "Illuminated Clay" (Ratti et al., 2004), consists of a flexible terrain model that can be modified by hand, a laser scanner and a projector. The laser scanner scans the modified surface and the impact of the modification on a selected parameter (e.g. slope, water flow pattern) is then projected as a color map on the surface in real time. The prototype system is located at the Media Laboratory at MIT and we have recently established a collaboration with its development team. If the system proves useful and effective we plan to seek federal funding to establish it as a research and education tool at NCSU. The support for this collaboration is leveraged by funding from U.S. Army Research Office. An illustration this system's application for an area around SECREF (Lake Wheeler NCSU experimental farms) is described by Mitasova et al. (submitted) and at a web site http://skagit.meas.ncsu.edu/~helena/wrriwork/tangis/tangis.html

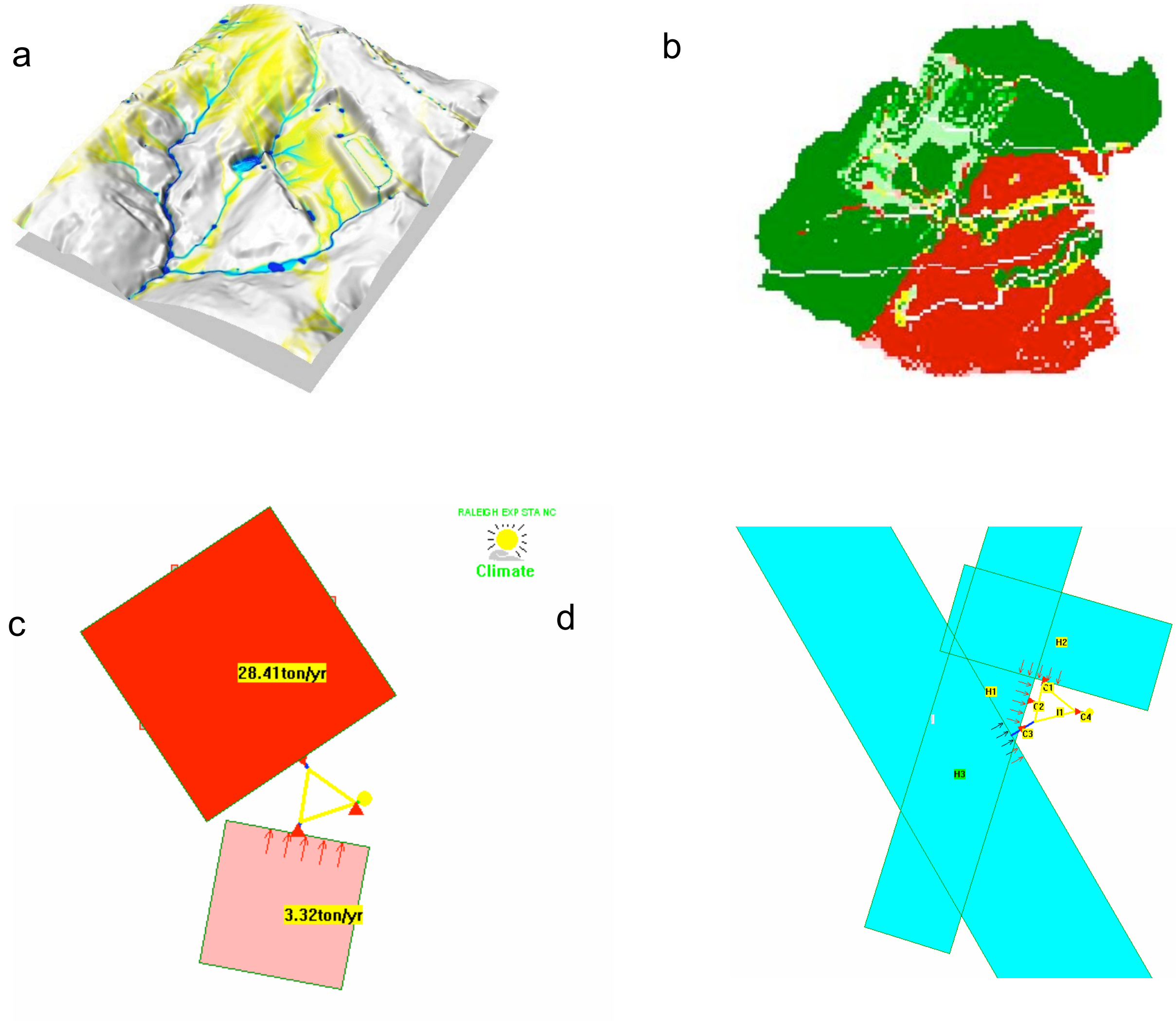

Figure 9. Spatial representation in a) SIMWE water flow shows the complexity of water flow after construction that controls the spatial pattern of erosion b) GeoWEPP (Moore et al. 2004), erosion/deposition maps for different scenarios in the entire area shown in Figure 5, red is high and green is low erosion; hillslopes are represented by pixels along flowpaths; c) watershed version of WEPP approximates hillslopes by tilted planes and water is further routed through channels and basins (Bd, 71% cecil (red), 29% appling (pink)); d) different representation that replaces the squares with wider and shorter rectangles, but also lowers the sediment yield estimates.

Figure 10a. Solid terrain model

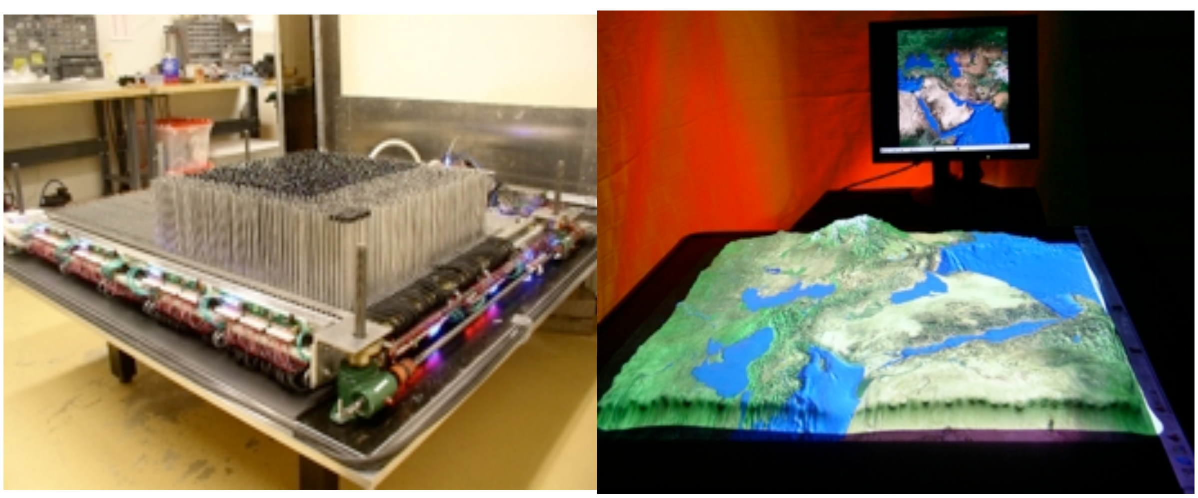

Figure 10b XenoMark: pin-based dynamic soild terrain model

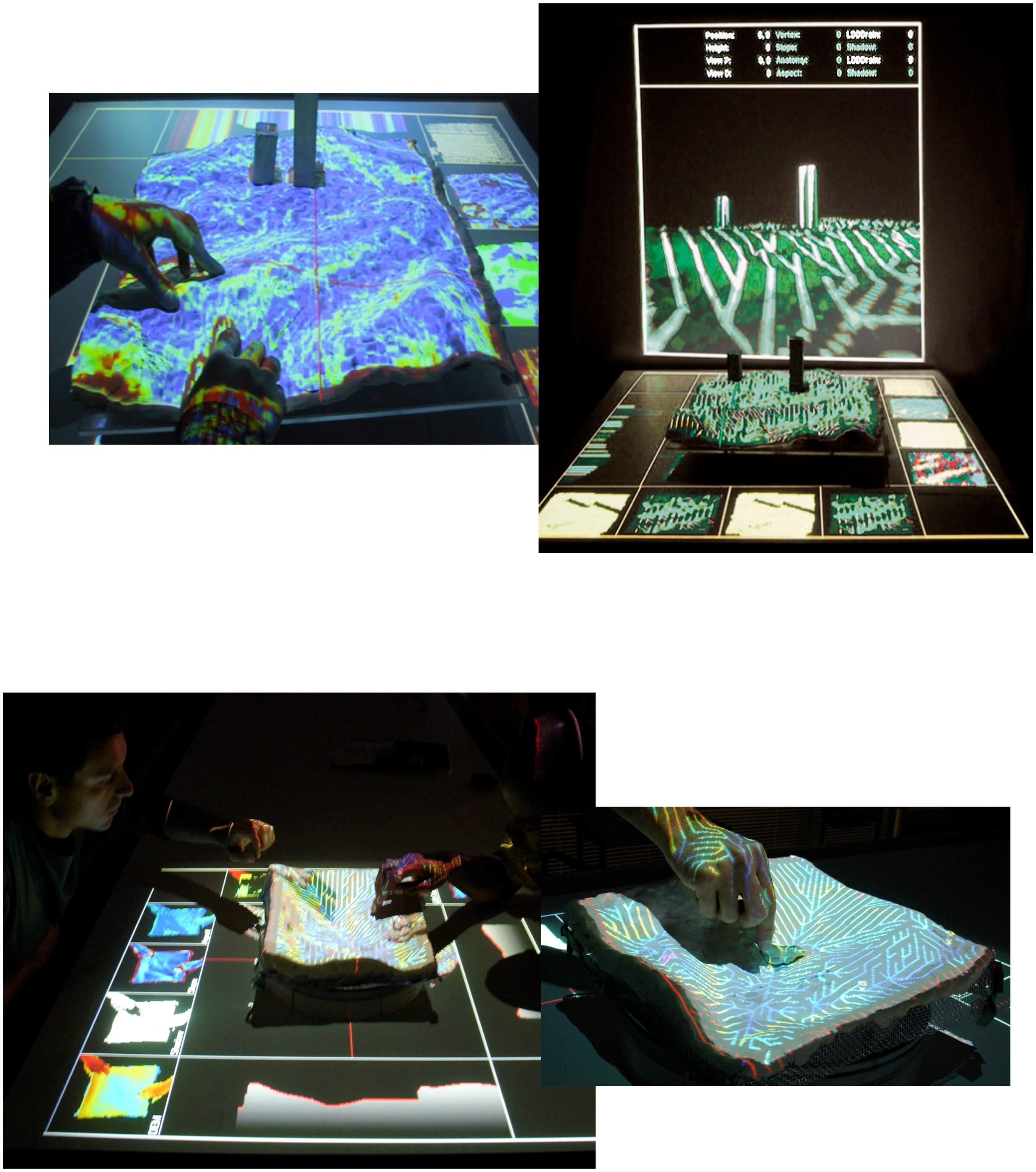

Figure 10c Illuminated clay that is being developed into a Tangible GIS. The two lower images show manipulation of a solid model of an area around SECREF that included creation of a basin and addition of a checkdam. The impact of modification on the flow direction pattern is projected in real-time on the surface, color shows the slope.

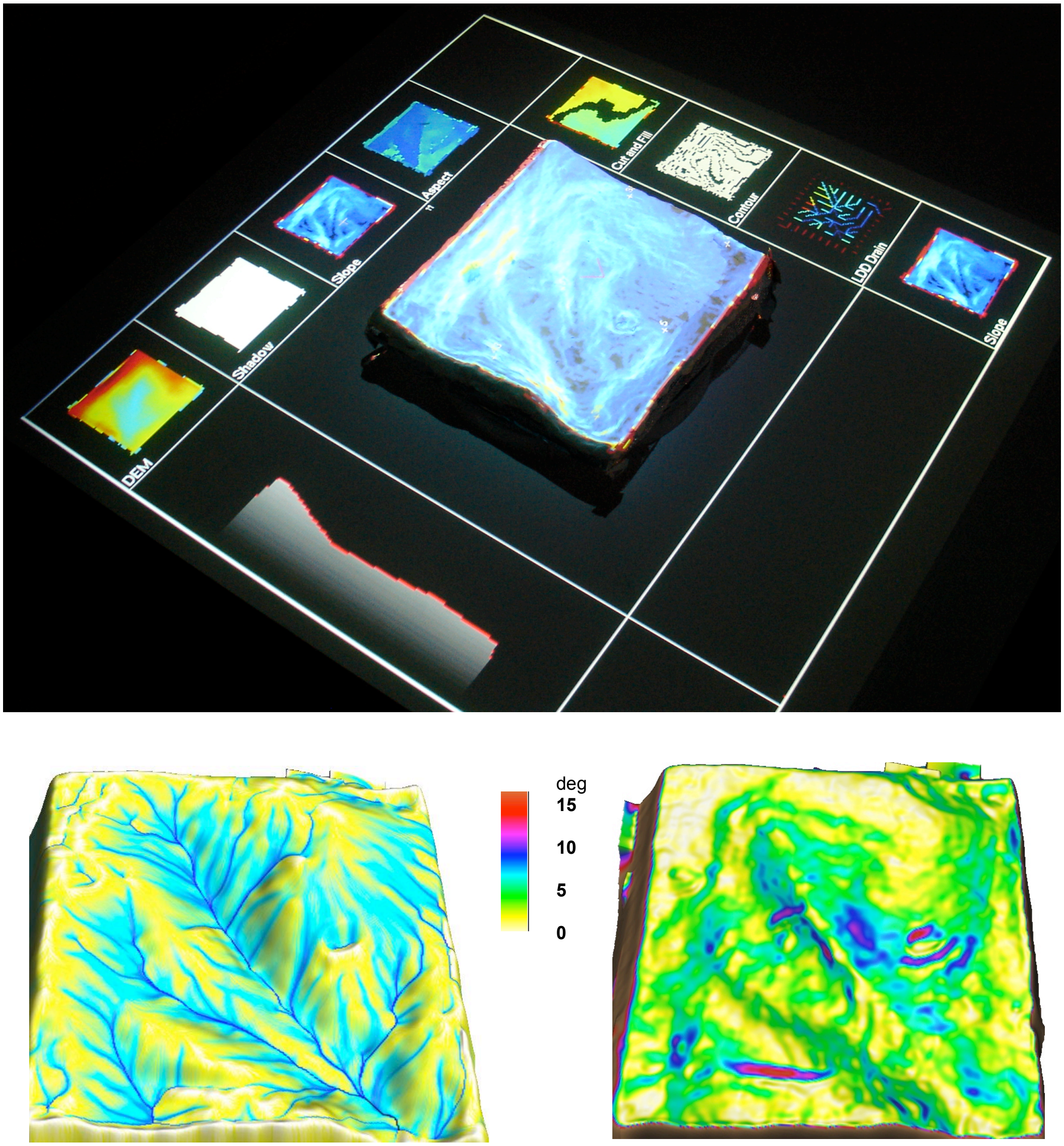

Figure 10d Clay model of area near SECREF placed in the Illuminated Clay environment. Lower two images show water flow pattern and slope map computed for the modified clay model after the scanned elevations were imported into GRASS GIS.

7. Conclusions and further research

Based on the analysis presented in this report, the following conclusions can be reached with respect to sediment and turbidity control systems on construction sites in North Carolina:

- The results confirm findings by other experimental and modeling studies that the current standard design of sedimentation basins does not provide adequate sediment control.

- This results suggest a need for (1) re-evaluation of the assumptions underlying the existing rules for sediment basin design, and (2) consideration of measures to bring the site conditions closer to the assumptions (e.g., mandatory baffles);
- Integration with storm water control measures emerged as the most cost effective approach for improving the environmental effectiveness of the current sediment control

- Spatial simulation for phased construction demonstrated that the effectiveness of this approach is highly site specific. The number and type of measures required is greatly dependent on configuration of terrain and grading. Phased development may well require the same number of structures as without phased development along with additional costs due to scheduling of the construction.

Further future work will:

- Investigate the optimal sedimentation basin design that incorporates realistic conditions, such as turbulent and unstable flow, erodible banks. Compare effectiveness of increased depth, baffles, length-to-width ratio in terms of minimizing flow turbulence
- Investigate the most effective approach to enhance enforcement. Based on the results of Reice and Andrews (2000), the cost effectiveness of enforcement can be improved by creating an erosion potential map for areas with potential for development (RUSLE and USPED may be enough for this). Enforcement can then target construction sites in the high risk areas in particular.

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